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Physiological and Manikin Evaluations of Submarine-Deck Exposure Suits (U)

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Navy Clothing and Textile Research Facility (NCTRF) compared the standard (STD) submarine-deck exposure suit (SDES) with a more watertight, modified (MOD) version. The suits were compared on the thermal manikin, in both a static and a dynamic mode, and on human test subjects in both air and water. For the thermal manikin evaluations, the clo values were similar for both versions of the SDES in calm (0.4 clo) and simulated rough water (0.3 clo), and in air, with (2.4 clo) and without (2.8 clo) a 6.7 m/sec (15 mph) wind. For the water tests, four subjects were immersed in 7.2°C water, with an ambient temperature of 0°C and minimal wind, for 2 hours. During the immersion, they floated quietly on the water in a horizontal position. For the air tests, the same subjects were evaluated for 3 hours in an environment of -6.7°C, with a wind velocity of 4.5 m/sec. For the first and third hours, the subjects sat in a chamber with minimal movement permitted to keep hands and feet warm. The second hour consisted of walking on the treadmill at 1.56 m/sec. For both the water and air tests, no significant differences between the STD and MOD suits were

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noted for rectal temperature, cooling rate, skin temperature, heart rate, and predicted survival time. Subjectively, it was reported that the modified suit had a slower rate of water seepage into the suit, but this was not projected into slower body cooling rates. (U)

We concluded that the more watertight version of the SDES did not provide additional protection in cold water or cold air, probably because, despite the seals, water was still able to flow through the garments, thereby increasing convective and conductive heat loss. (U)

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PHYSIOLOGICAL AND MANIKIN EVALUATIONS OF SUBMARINE-DECK EXPOSURE SUITS

INTRODUCTION

The following Navy Clothing and Textile Research Facility (NCTRF) report describes the physiological and thermal manikin comparisons of the standard (STD) and the modified (MOD) submarine-deck exposure suits (SDES). The purpose of this study was to determine if the MOD suit provided additional protection from cold environments, particularly for individuals immersed in water.

The SDES suit is a cold-weather garment which, because of its buoyancy, is used during topside operations on submarines to protect the wearer against any combination of wind, wet, and cold conditions. The SDES is an impermeable one-piece coverall with attached hood. The garment consists of an outer shell of coated nylon, a liner of uncoated nylon taffeta, and an interlining of expanded plastic foam. In the STD version, the sleeve and leg bottoms and waistband have hook-and-pile tape-fastener adjustments. The front closure is a zipper from neck to crotch with a protective flap.

The STD suit was modifed to minimize water seepage into the coverall when the wearer is immersed in water. Modifications included: 1) an environmental barrier zipper; 2) glued seams strapped with 3/4" bias tape; 3) addition to the inner liner of closed cell neoprene foam wristlets and anklets, which fasten with Velcro; 4) addition of a plastic zipper to the outer shell of the coverall and to each sleeve and leg; 5) addition of a closed cell neoprene foam collar to the inner liner; and 6) addition of a throat tab to the outer shell.

The physiological evaluation of these garments centered on the ability of the garments to keep a person from becoming hypothermic when inactive in cold water or cold air. The manikin evaluation provided information regarding the expected heat loss through the garment when it was immersed in still or moving water. The moving water was included to represent rough seas in which water would continuously flush through the garment.

METHODS AND PROCEDURES

Thermal Manikin Evaluation

The STD and MOD SDES were tested under identical conditions in water and in air. For all tests, the manikin was dressed in thermal underwear, utility uniform, wool socks, extreme-cold-weather boots, impermeable, neoprene mittens, and either the STD or the MOD SDES. With the STD ensemble, the mittens were worn under the sleeve. With the MOD ensemble, the mittens were worn over the neoprene wristlet seal and under the sleeve. All seals were securely fastened. For the air evaluation, the manikin was placed in the center of a controlled environmental chamber set at 21°C. Two tests were conducted at this temperature, one with a minimal wind speed of 0.8 m/sec (1.7 mph) and another with a 6.7 m/sec (15 mph) wind.

Following the air tests, the manikin was moved to the NCTRF pool area where, dressed in the same ensemble, it was immersed to the neck in still water of 17.5°C. After sufficient time for equilibration was allowed, the clo values were obtained. The manikin was then relocated to a specially designed water tank, which is depicted in Figure 1, in which water was pumped from the feet to the head of the manikin. This flow arrangement provided maximal forcing of water through the garment seals of the arms and legs.

The velocity of the water at the manikin's neck, wrists, and ankles was obtained by dividing the volume rate of flow (obtained from interpolation of the pump flow curve using the measured adjusted back pressure produced by adjusting the in-line gate valve) by the cross-sectional area of the manikin at the neck, wrist, and ankle regions. For this dynamic evaluation, test conditions were as follows:

Water temperature = 17.5°C

Manikin temperature = 36.0°C

Average flow velocity 1 = 0.15 m/sec (0.12 m/sec at the ankles; 0.11 m/sec at the wrists; and 0.22 m/sec at the neck)

Average flow velocity 2 = 0.42 m/sec (0.34 at the ankles; 0.31 m/sec at the wrists; and 0.62 m/sec at the neck)

Flow velocities 1 and 2 corresponded to a mild and a moderate sea state, respectively. To obtain a heavy sea state condition, we would have needed pumps with flow capacity of approximately 5700 liters per minute (1500 gallons per min), which would have been difficult to obtain and to use in our laboratory.

The manikin was first tested under the simulated mild sea state. Following equilibration, at which time the clo value was obtained, the water flow was increased to simulate the moderate sea state. A repeat of the mild sea state subsequently showed no change in the clo value. This sequence was followed for both SDES.

Physiological Evaluation

Four men, who were deemed physically fit and had reported no previous cold-related injuries, were selected from the U. S. Army Natick Research, Development and Engineering Center test subject platoon. After having the nature of the study and its possible risks explained, they signed the informed consent statement. Their mean ± S.D. physical characteristics were as follows: age, 23.0 ± 2.7 years; height, 181.3 ± 2.9 cm, weight, 82.9 ± 11.9 kg; surface area, 2.03 ± 0.14m^2.

The clothing ensembles we evaluated consisted of standard thermal underwear, the two-piece utility uniform (denim trousers and chambray shirt), either the MOD or STD SDES, wool socks, extreme-cold-weather boots, and Army cold-weather mittens.

Testing was conducted in cold air and in cold water. For the air tests, the ambient temperature was -6.7°C (20°F), with 50% r.h. and a 4.5 m/sec (10 mph) wind. In this environment, tests were 3 hours in duration. For the first hour, the individual was quietly seated in the chamber, with some movement permitted to prevent hands and feet from becoming cold. The second hour consisted of walking on the treadmill at 1.56 m/sec (3.5 mph). For the final hour, individuals again were seated quietly with only minimal movement permitted.

For the water tests, individuals were tested in 7.2°C (45°F) water. Air temperature in the chamber was 0°C (32°F), with a wind speed of <1 m/sec blowing across the surface of the water. Exposure was 2 hours in duration, during which time the individual lay horizontally in the water. Because of the buoyancy of the cold weather boots, the feet had to be wedged into the portholes in the water tank to reduce the horizontal flotation posture somewhat. In this way, water could flow through the seals, thereby testing their effectiveness. During the 2-hour exposure, the test subjects remained as still as possible with some movement permitted to prevent hands and feet from becoming unduly cold. The subjects normally rested their hands on their chest to keep them dry.

Preparation for all tests was the same. Prior to each exposure, the test volunteer was weighed nude and the rectal probe (Y.S.I. Series 400 thermistor) was inserted. For the air tests, copper-constantan thermocouples were attached to six skin surfaces, which were weighted according to the following formula: 0.070 (forehead) + 0.190 (lower arm) + 0.230 (thigh) + 0.160 (lower leg) + 0.175 (chest + back). In the water, ten skin surface sites were weighted as follows: 0.100 (cheek) + 0.125 (chest + back) + 0.070 (upper arm + lower arm) + 0.060 (palm) + 0.125 (medial thigh + lateral thigh) + 0.150 (calf) + 0.050 (foot).

For both the air and water tests, three electrodes were attached to the surface of the chest for continuous monitoring of heart rate with the EKG. For the air tests, rectal and skin temperatures were monitored continuously on a Hewlett Packard data acquisition system and values were printed every 2 minutes. For the water tests, the skin temperatures were measured every 5 minutes with a Kaye 36 channel data logger. Rectal temperature was monitored continuously with a Y.S.I. Model 49TA Digital Tele-Thermometer.

Exposures were planned to be 3 and 2 hours in duration for the air and the water tests, respectively. However, the test was terminated if any of the following occurred: rectal temperature <35°C; any skin temperature <4°C; loss of signal from the rectal thermistor; or extreme subjective distress of the test volunteer.

The data were analyzed with a repeated measures analysis of variance, using the different SDES as treatment 1. Duncan's multiple comparison test was utilized as a post-hoc evaluation if significant ($p<0.05$) F-values were found.

RESULTS

Thermal Manikin Evaluation

Clo values for the STD and MOD suits were as follows:

	SEA STATE			AIR	
	Calm	Mild	Moderate	Wind	No Wind
Clothing					
STD	0.4	0.3	0.3	2.4	2.8
MOD	0.4	0.3	0.3	2.4	2.8

Using a mathematical model, tolerance predictions based on the clo values of 0.3 and 0.4 were made by Dr. Eugene Wissler of the University of Texas (personal communication). For a 75 kg individual of average body fat (average skinfold thickness = 8.4 mm) and a progressive metabolic rate from 120 to 370 W, tolerance time in a water temperature of 7.2°C and an air temperature of 0°C would be 2 and 3 hours for the dynamic and static measurements, respectively. Tolerance time was predicted on the basis of arterial temperature decreasing to 34°C.

Physiological Evaluation

Water Evaluation. All subjects successfully completed the 2-hour exposures in the cold water. No significant differences in heart rate were observed between the STD and MOD suits for the 2-hour water exposure. Mean ($\pm$ S.E.) heart rate for the four subjects lying in the water and wearing either SDES decreased from 90 $\pm$ 3 beats/min to 84 $\pm$ 3 beats/min over the 2 hours ($p>0.05$).

As seen in Figure 2, rectal temperature (T_{re}) decreased in a similar manner when either the STD or the MOD suit was worn, and no significant differences were evident between the suits at any time. During the course of the 2-hour water immersion, mean rectal temperature significantly decreased 0.95°C and 0.96°C for the STD and the MOD suits, respectively; the decrease was similar in both SDES. The rate of fall in T_{re} was calculated by the least squares method over the linear portion of the rectal temperature curves (from 30 to 120 min). The mean cooling rate was 0.61 $\pm$ 0.13°C/h and 0.64 $\pm$ 0.10°C/h for the STD and the MOD suits, respectively ($p>0.05$).

Figure 3 depicts mean skin temperature ($\bar{T}_{sk}$) changes over time for the two suits. At the end of the 2-hour exposure, $\bar{T}_{sk}$ was 21.3°C and 21.8°C in the STD and the MOD suits, respectively ($p>0.05$). The rate of decline of $\bar{T}_{sk}$ was calculated over the first 30 minutes of exposure. (This time, rather than the entire 2-hour period, was used because the greatest decline took place by 15-30 min of immersion.) With the STD suit, the mean decline of $\bar{T}_{sk}$ over the first 30 min was 8.6 $\pm$ 1.4°C, which wss not statistically different from the decline of 7.4 $\pm$ 1.2°C with the MOD suit.

Subjectively, the test volunteers named the MOD suit as their choice for water immersion. They reported that the water flushed through the MOD garment more slowly than with the STD suit. With both suits, there were complaints that the groin area cooled very rapidly; and in one case, the test had to be terminated because of severe discomfort. The subjects also complained that in the MOD suit, the neoprene collar with Velcro closures was essentially useless because it could not close properly. They thought the neck area was very uncomfortable with the attached collar. Other comments included the suggestion that buoyancy be added to the neck region so that it would be easier to keep the head out of the water. Additionally, it was recommended that more insulation be added to the hood and that a better seal be found to keep the water out of the hood.

Air Evaluation. All individuals completed the full 3-hour cold exposure without reaching the objective or subjective termination points. Metabolic rate was predicted to be 302 W/m^2 during the walk and 70 W/m^2 during the rest period. (These values are based upon a previous cold-weather evaluation of protective clothing following an identical protocol (1).)

As with the water test, there were no significant differences between the two suits in any of the measured physiological parameters. Heart rate responses followed similar patterns in the MOD and STD suits. With both garments, initial heart rate decreased approximately 10 beats/min to 66 beats/min during the first hour of rest. Exercise increased heart rate approximately 38 beats/min to a final exercise value of 105 beats/min. During the last hour of rest, heart rate decreased approximately 40 beats/min to a final value of 62 beats/min.

As seen in Figure 4, T_{re} decreased 0.04 and 0.19°C in the STD and the MOD suits, respectively, over the first hour of rest ($p>0.05$). With exercise, T_{re} rose 0.71° and 0.82°C when the STD and the MOD suits, respectively, were worn. The rise in T_{re} was not significantly different between suits. During the final hour of rest, T_{re} decreased to identical values (36.9°C) in the two different suits.

Figure 5 depicts the $\bar{T}_{sk}$ changes during the cold exposure. Skin temperature declined approximately 4°C in both the STD and MOD suits over the first hour of rest in the cold. During the exercise period, $\bar{T}_{sk}$ rose 1.5°C with the STD suit and 2.6°C with the MOD suit ($p>0.05$). Although the rate of decline of $\bar{T}_{sk}$ during the final hour was the same in both suits, $\bar{T}_{sk}$ remained 1°C higher in the MOD suit than in the STD suit. This difference, however, was not statistically significant.

Subjectively, the test volunteers felt that either suit would provide adequate protection against cold, particularly if some facial protection were available. With the MOD suit, however, they complained that the Velcro closures at the ankles opened as soon as exercise was begun. Additionally, the neck closure was considered to be somewhat restrictive.

DISCUSSION

Physiological Evaluation

The intent of this study was to determine whether the MOD SDES provided better cold-water and cold-air protection than the STD. The results of the test, however, showed no significant differences in any of the measured physiological parameters in either water or air. Static and dynamic manikin evaluations in both water and air also revealed no differences in resistance to heat loss (clo values) between the two versions of the suit.

Of particular concern in evaluating cold-protective garments, especially as related to cold-water survival, is the cooling rate of the body. Both the MOD and STD suit were found to have identical rectal temperature cooling rates of approximately 0.6°C/h in water. As skin temperature declines are directly related to differences in rectal temperature cooling rates (2,3), the linear decline in skin temperature found in this evaluation during water immersion was also similar in both suits.

Survival times in cold water can be estimated from the mean rectal temperature cooling rates. Projections based on four test subjects, however, should be made with caution, because the subjects used in this evaluation may not be representative of the entire Navy population. In particular, these subjects were about 9 kg heavier than the average sailor (approximately 74 kg), and may have had a higher percentage of subcutaneous body fat. Since body fat provides a static layer of insulation which acts to reduce heat flow from the body core to the skin surface (4,5,6), individuals with higher percentages of body fat would theoretically transfer, and ultimately lose, less heat from the body core. In addition, the survival times cannot be extrapolated to water temperatures other than the 7.2°C evaluated in this study. It is reasonable to assume, however, that cooling rates will be higher, and hence survival times shorter, in colder water.

The following assumptions must be made in predicting survival time (3): 1) cooling rates are linear beginning at 15-30 min (2,7,8); 2) initial rectal temperature is 37.5°C; 3) death due to cardiac arrest will occur at a core temperature of 25°C (9,10); 4) with garments lacking self-righting buoyancy, death will occur from drowning, secondary to hypothermia-induced unconsciousness, at a core temperature of 30°C; 5) survivors are able to keep their heads above water in rough seas until unconsciousness occurs at a core temperature of 30°C.

Survival times were calculated both for hypothermia-induced cardiac arrest at a core temperature of 25°C and for hypothermia-induced unconsciousness at a core temperature of 30°C. Assuming a constant linear drop in rectal temperature, similar to that occurring from 30-120 min (see Figure 2), cardiac arrest will occur in approximately 20 hours with the STD and MOD suits. Unconsciousness will occur at approximately 12 hours in both suits.

The question of calm versus rough seas is a significant one to consider in evaluations of water-protective garments. Protective clothing for both land and sea adds another layer of insulation to the body, which will act to reduce heat loss through the skin surface. In the water, a garment which allows water to continuously flush through will not be as protective in diminishing heat loss as one which either totally prevents water entrance ("dry" suit) or fits tightly enough to trap a layer of water against the skin ("wet" suit). A recent study (3) has shown that in both calm and rough seas, compared to looser fitting water-protective garments, tighter garments reduced the flushing of cold water and thus reduced heat loss, as manifested by higher skin temperatures and lower core cooling rates.

The MOD and STD SDES allowed flushing of water through the garment. A great deal of water dripped from both suits when the volunteers exited the pool. Subjective comments indicated that, although they felt flushing of water was a significant problem with both suits, it was less severe with the MOD suit. While this may have been the case, however, under the design of this study, no physiological advantages were noted for the MOD suit.

A more stressful evaluation to forcefully flush water through the garment may have yielded a better performance of the MOD over the STD suit. In a Coast Guard study (3), the Boatcrew coveralls, a garment similar in design and thickness to the STD SDES, were evaluated with a variety of other anti-exposure suits in both calm and rough water of approximately 10°C. Compared to the calm seas, rectal temperature cooling rate doubled (from 0.98 to 1.96°C/h) when the individual was immersed in rough seas. (Note: This study used much leaner subjects than we did. Hence the absolute cooling rates in the two evaluations cannot be compared.) Despite the doubling of the cooling rate, however, time to cardiac arrest in 10°C water was predicted to be 6.4 hours; predicted time to unconsciousness was 3.8 hours.

If we assume that rough seas would double the cooling rate to 1.25°C/h in the STD ensemble, predicted survival times to cardiac arrest and to unconsciousness would be 10.0 and 6.0 h, respectively, for the subjects we evaluated.

In rough seas, wave action would significantly reduce the insulation provided by either SDES garment because of the constant flushing of cold water through the suit (11,12). Only survival suits and custom-fitted wet suits showed no degradation in performance when tested in rough compared to calm seas (3). In addition, waves would necessitate physical movement to maintain uprightness in the water to prevent drowning; this would further increase convective heat loss. Survival times would therefore be reduced in rough compared to calm seas.

The design of both SDES, coupled with the buoyancy of the cold-weather boots, caused the subjects to float almost horizontally on the water. Horizontal flotation is not optimum for prolonged survival, because this position allows waves to break over the survivor's face and head and also facilitates rolling movements in very heavy seas. Wetting of the head and neck region would greatly increase total body heat loss (4, 13, 14). Because of the drawbacks to horizontal floating, it would seem warranted to somewhat reduce buoyancy in the lower portion of the SDES. However, the suits are expected to be worn with a life preserver to obtain proper flotation attitude. We did not test with a life jacket, but this may have reduced the horizontal flotation somewhat.

Comparison Between Physiological and Manikin Evaluations

Results from the manikin evaluations indicated no differences in resistance to heat loss between the two SDES. Using Wissler's mathematical model, predictions for survival in a water/air temperature combination of 7.2°C/0°C were made from the measured clo values. In still water (0.4 clo), the survival time would be 3 hours; in moving water (0.3 clo), 2 hours. The tolerance data from the physiological evaluation and the manikin tests cannot be directly compared because the size of test subjects and the body position in the water differed between the two evaluations. For the manikin predictions, Dr. Wissler assumed an average body fatness and a weight of 75 kg. While we did not measure body fat, our subjects were significantly heavier at 83 kg and subjectively appeared to have above average body fat. They should therefore have cooled more slowly and would have shivered less than the "ideal" group from the predictions. Moreover, the measured clo value from the manikin test did not accurately reflect the body position of the test subjects during the physiological evaluation. When the manikin was immersed in the water, it was weighted down somewhat so that only the head of the manikin was exposed to the air. The test subjects, however, were not weighted down; and because of the inherent buoyancy of the garment and the cold-weather boots, they tended to float horizontally on the surface of the water. Additionally, the subjects rested their hands on their chests, while the manikin's hands were completely immersed in the water. We estimated that only about 50% of the subjects' skin surface was actually losing heat to the water.

When the heat transfer equations are worked backwards, the clo value of the ensemble, as worn in the water by the test subject, can be detemined from the physiological data. Assuming a metabolic rate of 203 W to account for shivering heat generation and using the measured changes in mean body temperature from 30-120 min, we can calculate clo as 0.88 and 0.80 for the STD and MOD suits, respectively. When these clo values were run on the computer model using the actual physical characteristics of our subject sample in the same environmental conditions, tolerance time to an arterial temperature of 34°C was predicted to be 15 hours. After 2 hours of immersion, rectal temperature would be 36.0°C. This estimate of rectal temperature is somewhat higher than the actual physiological data demonstrated. At 2 hours, the mean T_{re} was 36.7° and 36.5°C for the STD and MOD suits, repectively.

From the results of the physiological tests and the apparently small effect on clo value produced by tightening up the closures, we wonder whether the importance of water penetration, as it affects thermal protection and tolerance time, might not be overemphasized. Our subjects said that flushing was less severe with the MOD suit, which has tighter closures, yet the rate of cooling in this suit was no less than in the STD suit. It seems that, even with poor closures, a suit might actually not exchange a large amount of water with the sea unless there was some sort of pumping action within the suit, as from body motion or wave turbulence against the suit, especially in a loosely fitting garment. Without a suit actually taking in cold sea water and returning warmed water, there is no mechanism for greatly increased heat dissipation. Random motion of already warmed water within the suit should not appreciably increase the wearer's cooling rate. Since path lengths for water flow into one closure and out another are long and have high resistance, it appears that water which does penetrate a closure will not, without pumping from within, move very far past the closure into the suit.

CONCLUSIONS

1. No differences in resistance to heat loss were found when the garments were evaluated on a heated thermal manikin. Clo value decreased 0.1 clo when the garments were tested in flowing water compared to the static evaluation. Predicted survival time for "standard" man was estimated at 2 and 3 hours in rough and calm seas, respectively.

2. Under the design of this evaluation, no differences between the MOD and the STD suits were noted in body cooling rates, skin temperature declines, and predicted survival times in 7.2°C water.

3. No differences in cold protection were noted between the STD and the MOD garments when the suits were evaluated in -6.7°C air. When the subjects exercised on the treadmill, the Velcro-closed, neoprene wristlets, anklets, and collar were found to be restrictive and annoying.

4. As reported by the test subjects, the modifications to the STD suit may have reduced flushing of water through the garment. This would prove advantageous in rough seas. However, even if the flushing of water through the STD suit doubled the rectal temperature cooling rate, the predicted time to unconsciousness would still be at an acceptable level (6.0 hours).

5. A major concern with the design of the garment is the horizontal flotation position which would increase the risk of drowning and increase heat loss because of physical efforts to remain afloat. Decreasing buoyancy in the lower portion of the SDES and/or wearing the suit with a life preserver as it is supposed to be worn operationally may provide a more optimal suit for survival.

APPENDIX A. ILLUSTRATIONS

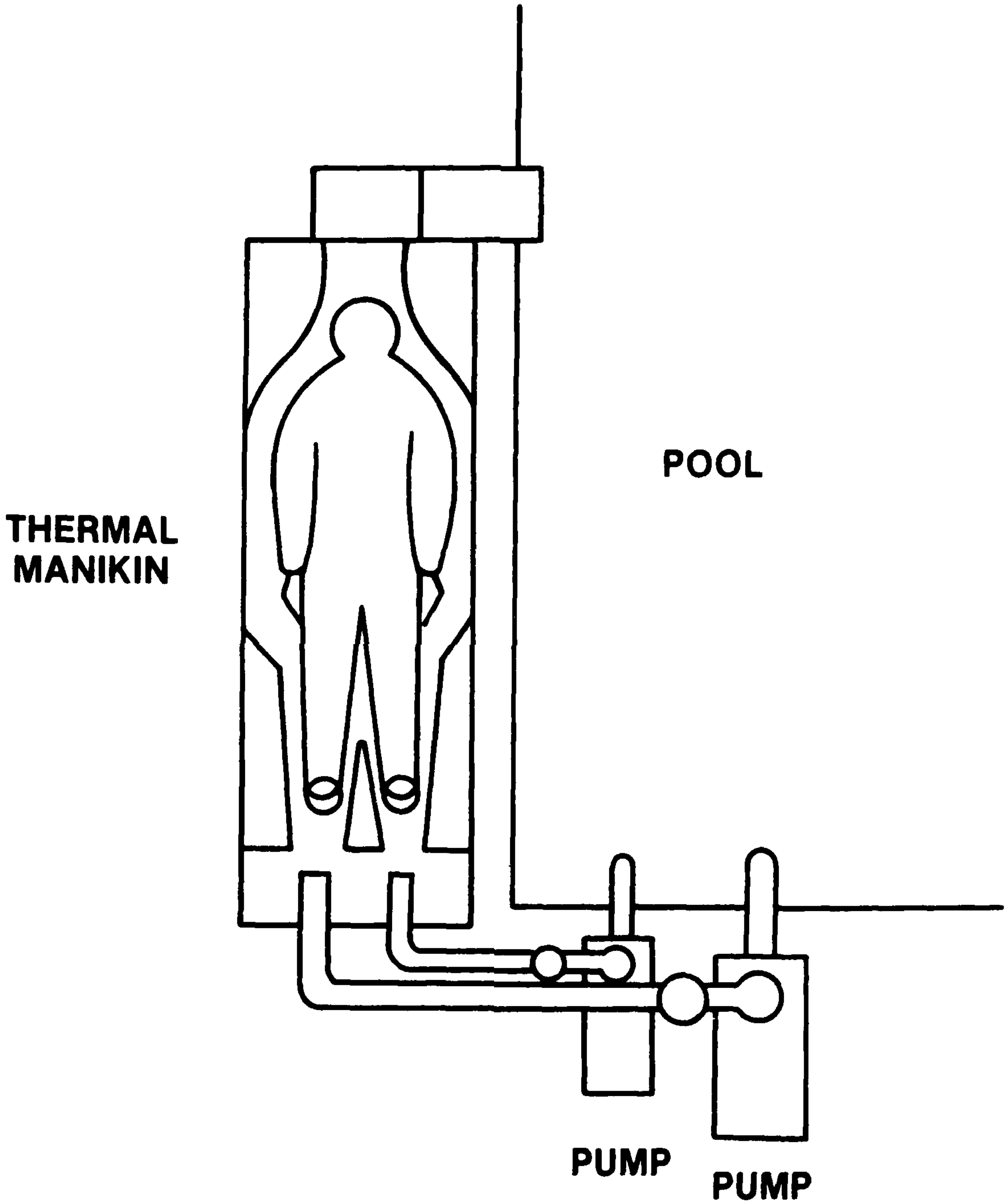

Figure 1. Schematic depicting test tank for dynamic thermal manikin evaluation

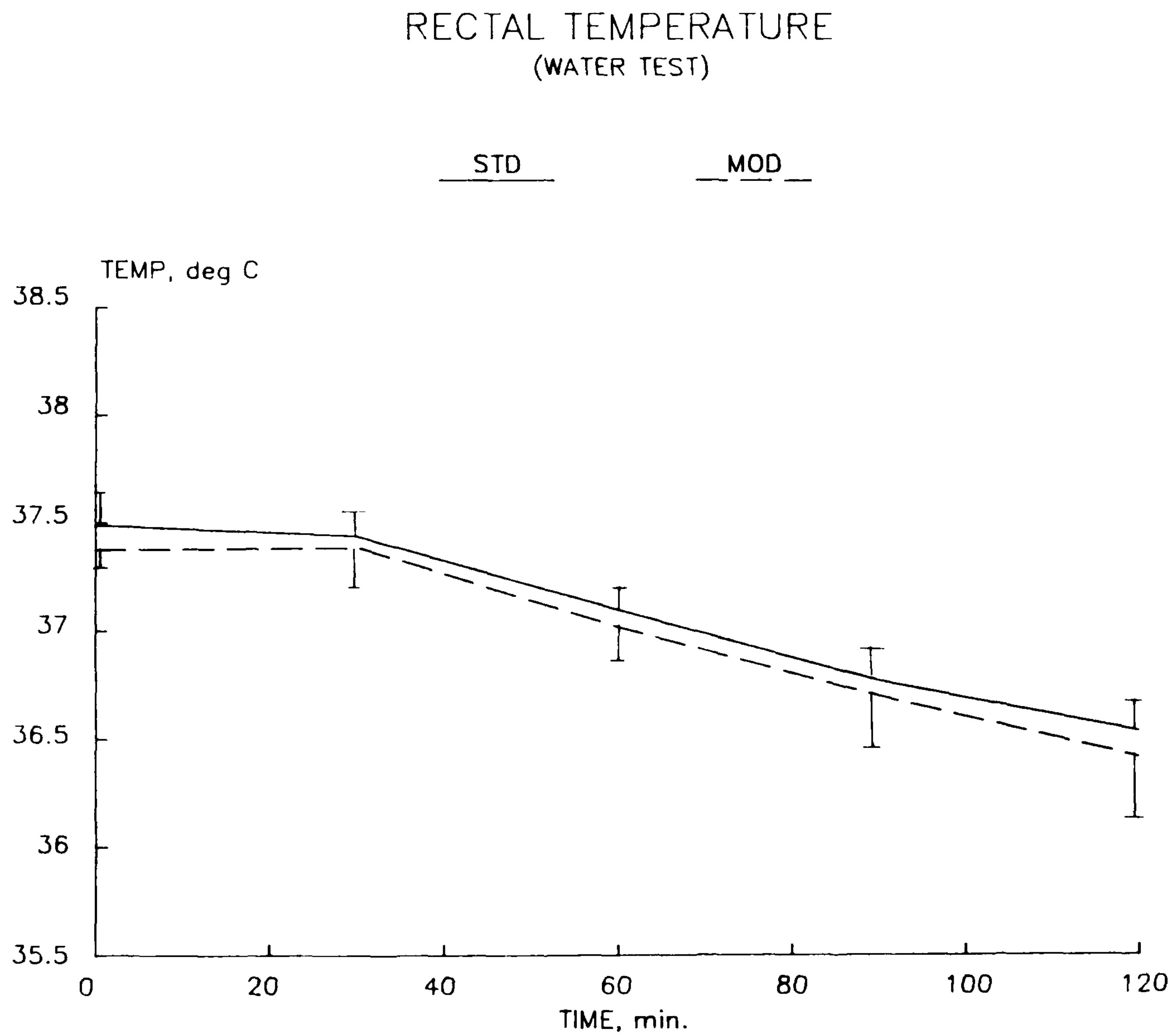

Figure 2. Rectal temperature values (mean ± S.E.) for the 2-hour water immersion test

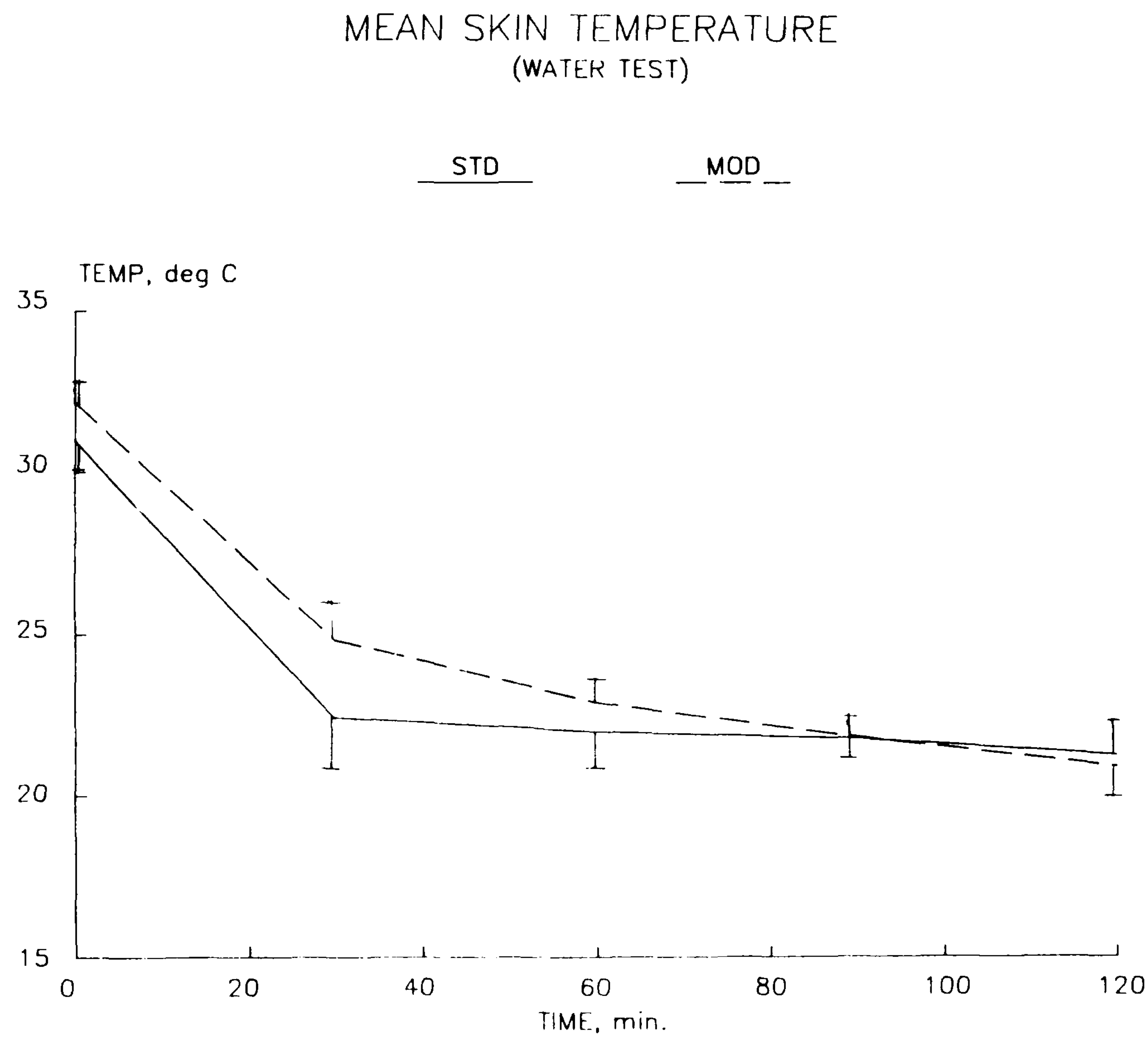

Figure 3. Mean skin temperature values (mean ± S.E.) for the 2-hour water immersion test

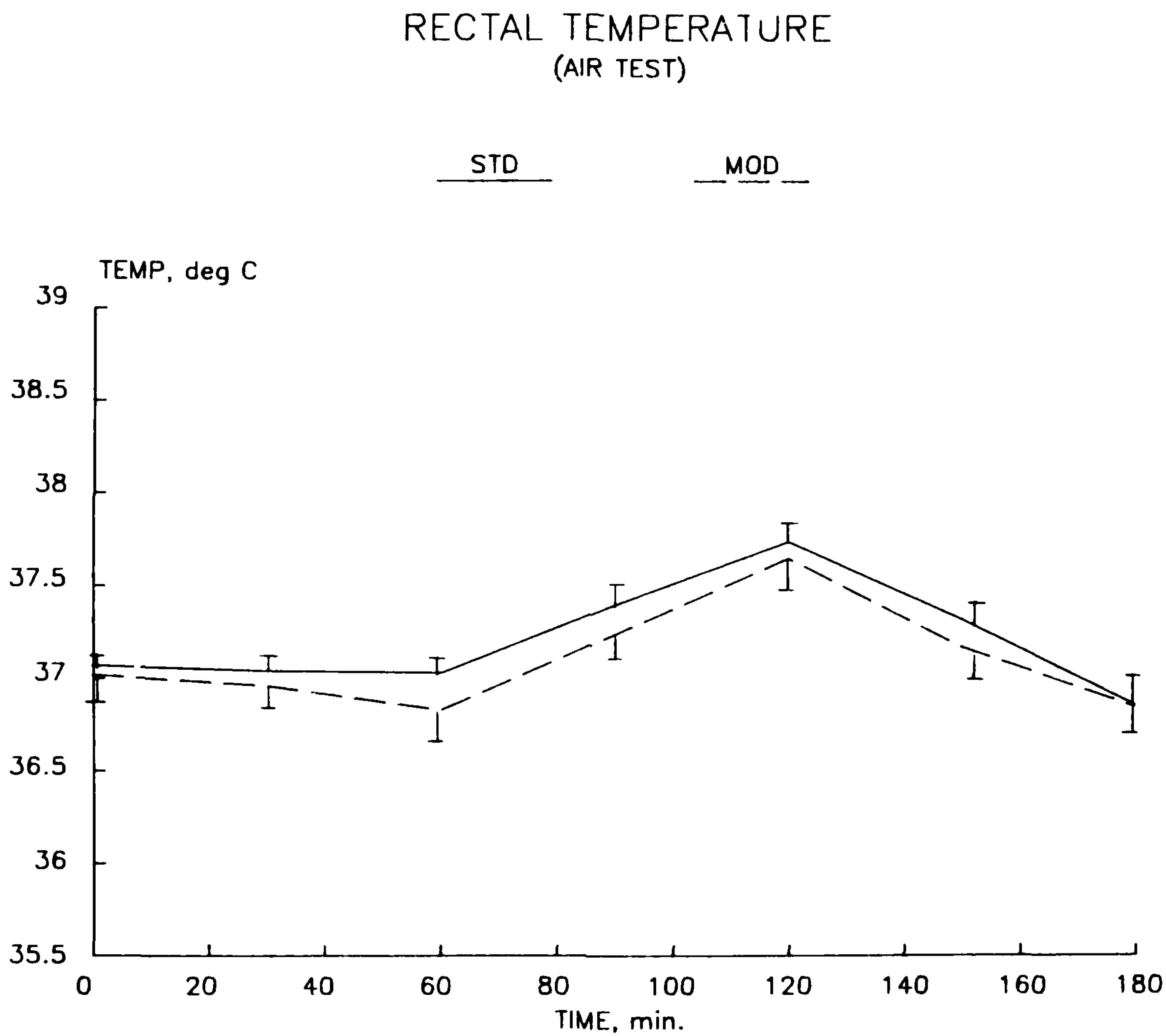

Figure 4. Rectal temperature values (mean ± S.E.) for the 3-hour cold air test

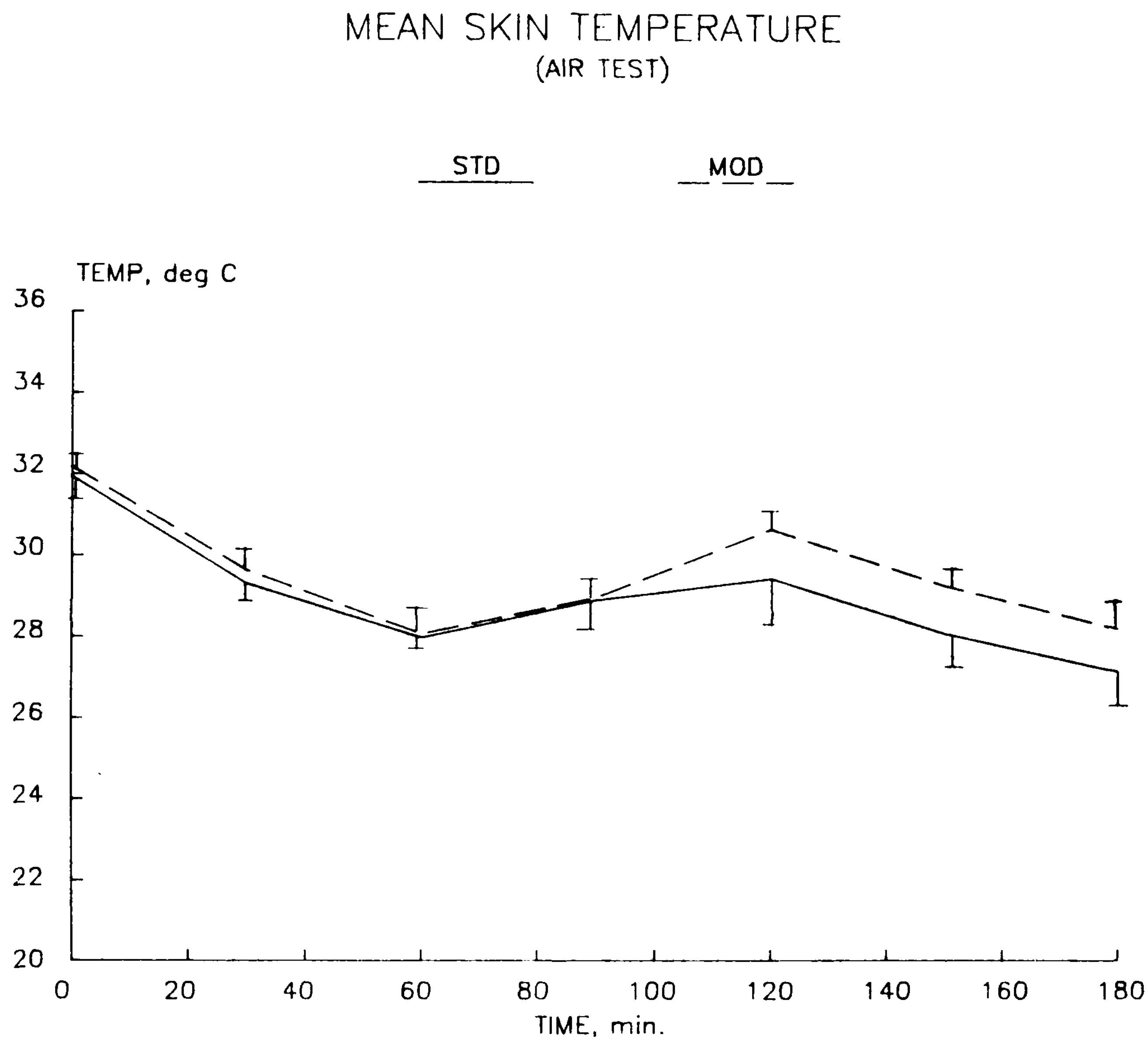

Figure 5. Mean skin temperature values (mean $\pm$ S.E.) for the 3-hour cold air test

Appendix B. References

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